Flexible, Real-Time Sensorized Grooved Pegboard Test Platform for Closed-Loop Neuromodulation

University of Colorado Anschutz Medical Campus

BIOElectrics Lab

Shayok Dutta, PhD[1,2], Adrienne Ellett, MS[1,2], Cristin G Welle, PhD[1,2]

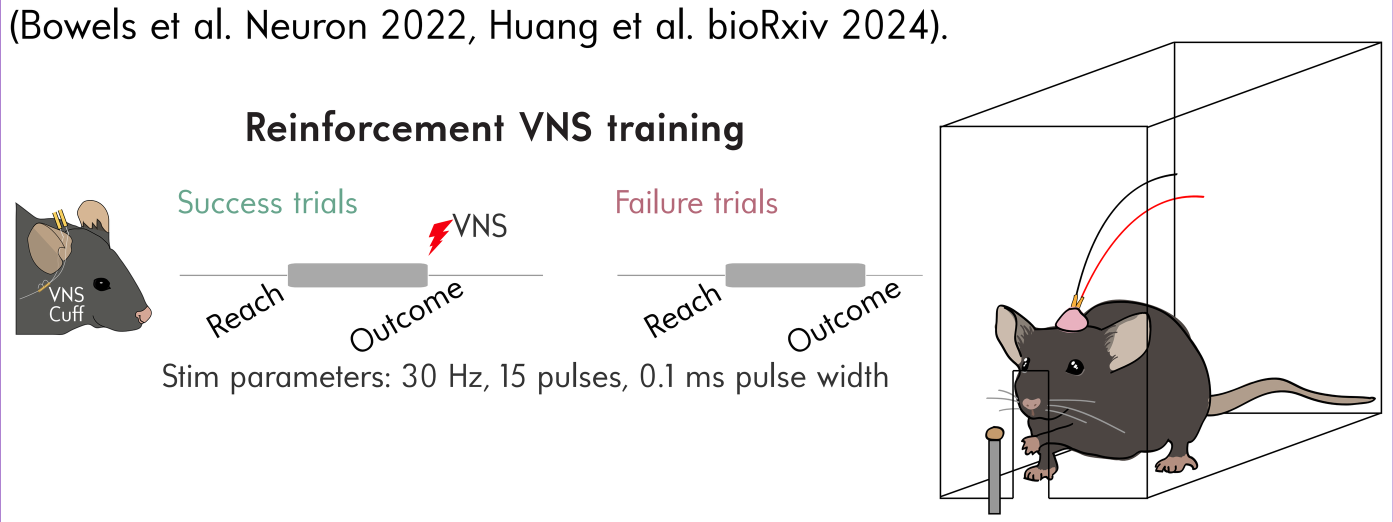
1. Department of Neurosurgery; 2. Department of Physiology and Biophysics, University of Colorado School of Medicine, Aurora, CO 80045

VNS to improve motor deficits in MS

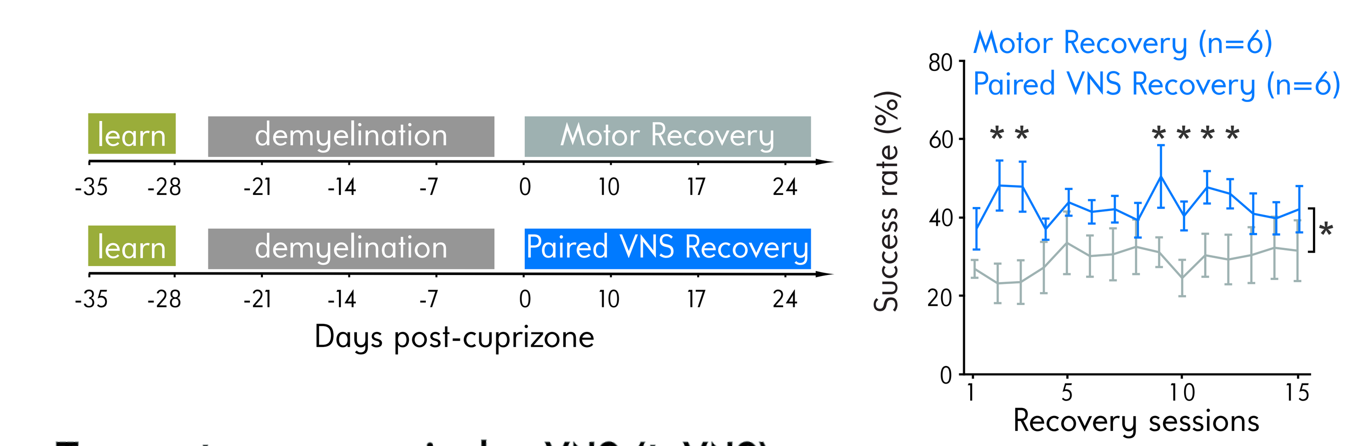
- **The Problem:** Restoring motor function after neurological injury or disease remains a significant clinical challenge. For many, including individuals with Multiple Sclerosis (MS), fine motor skill impairment is a major barrier to independence & quality of life.

- **The Gap in Treatment:** While current therapies for MS may reduce relapses, there is a significant unmet need for innovative approaches that actively promote functional recovery.

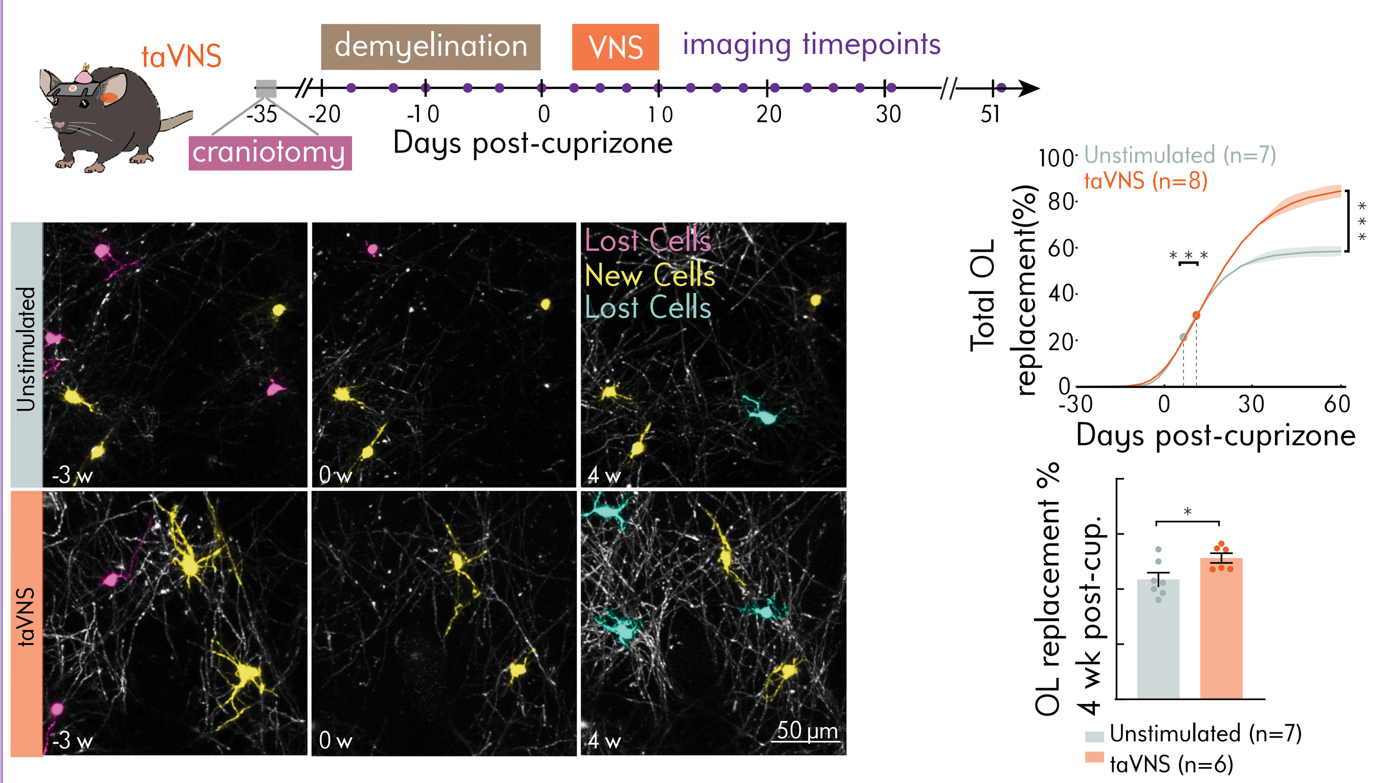
- **A Promising Solution?** Paired Vagus Nerve Stimulation (VNS), where stimulation is precisely timed with successful motor events in pre-clinical models, is a promising strategy to drive neuroplasticity and enhance functional recovery (Bowels et al. Neuron 2022, Huang et al. bioRxiv 2024).



Reinforcement VNS restores motor function in mouse model of multiple sclerosis



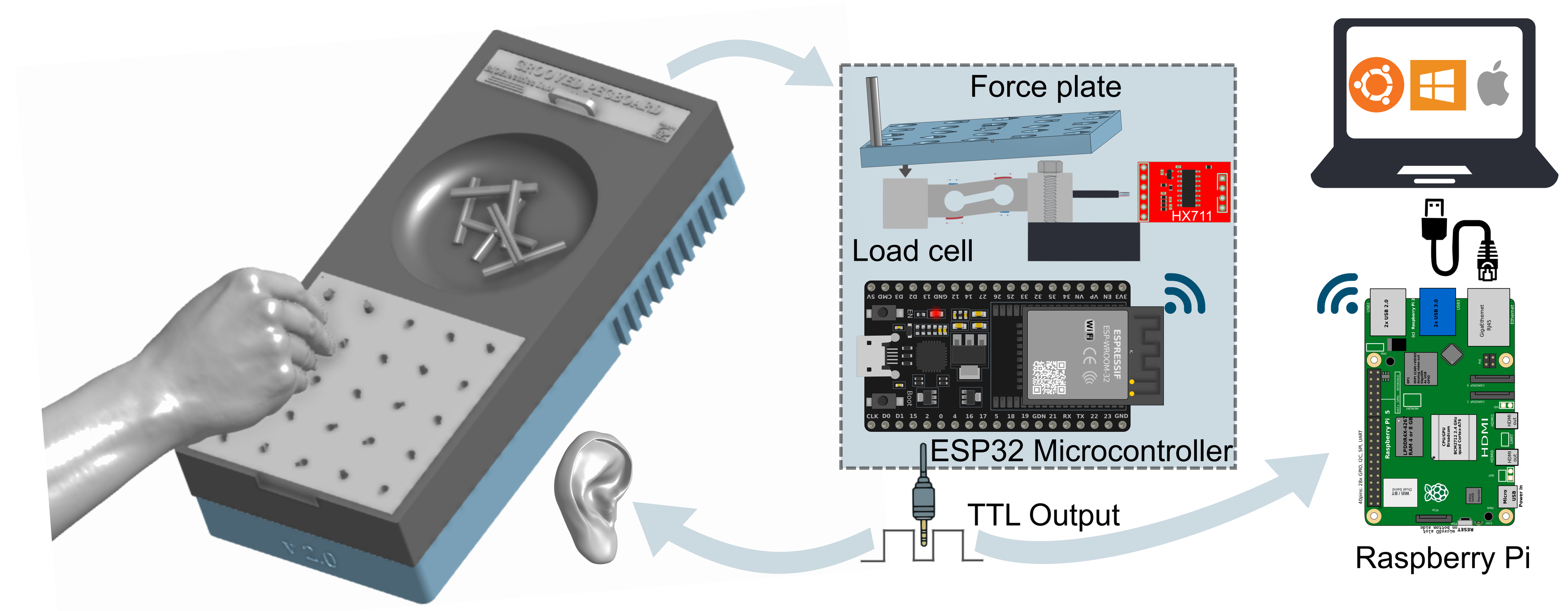
Transcutaneous auricular VNS (taVNS) promotes remyelination after myelin loss



- **The Technological Hurdle:** The Grooved Pegboard Test (GPT) is a validated measure of fine motor dexterity. However, its standard clinical usage relies on manual timing, preventing its use in a real-time, closed-loop therapeutic application such as success-paired VNS.

Objective: Develop and validate a reliable system for real-time, closed-loop VNS on fine motor tasks in humans

Closed-loop system for taVNS with fine motor task



Our platform integrates a standard GPT with a custom electronics enclosure.

- **Sensing:** The enclosure houses a "force plate" mounted on a 300g load cell **(Uxcell 6160-300g)**. This load cell detects the physical force applied when a peg is placed.

- **Processing:** The load cell's signal is sent to an **HX711 amplifier** (sampling at 80 Hz) and then processed by an **ESP32 microcontroller**. The ESP32 runs the real-time detection algorithm.

- **Control & Data Logging:** A **Raspberry Pi** acts as the central control unit. It receives the trigger pulse for taVNS and weight data from the ESP32, synchronizes them, logs the data, and hosts the experimenter interface.

- **Interface:** An experimenter controls the session from a networked laptop via an SSH connection to the Raspberry Pi that launches a graphical user interface on a local host network.

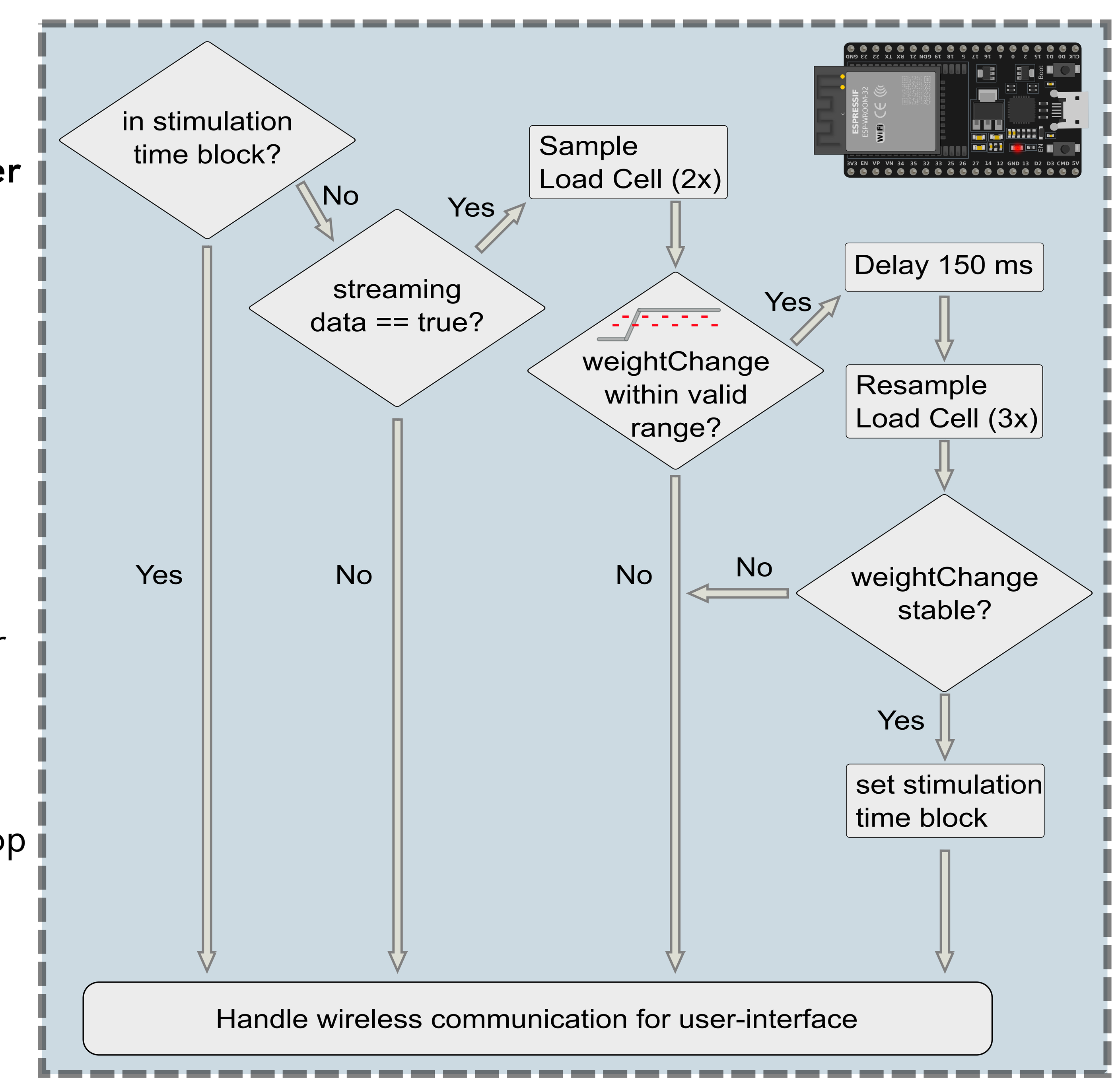
Real-time detection algorithm

ESP32 µController Algorithm:

1. Initial Sample
2. Stabilization Delay (150 ms)
3. Confirmation Sample
4. Trigger TTL 1 second pulse for taVNS

Performance:

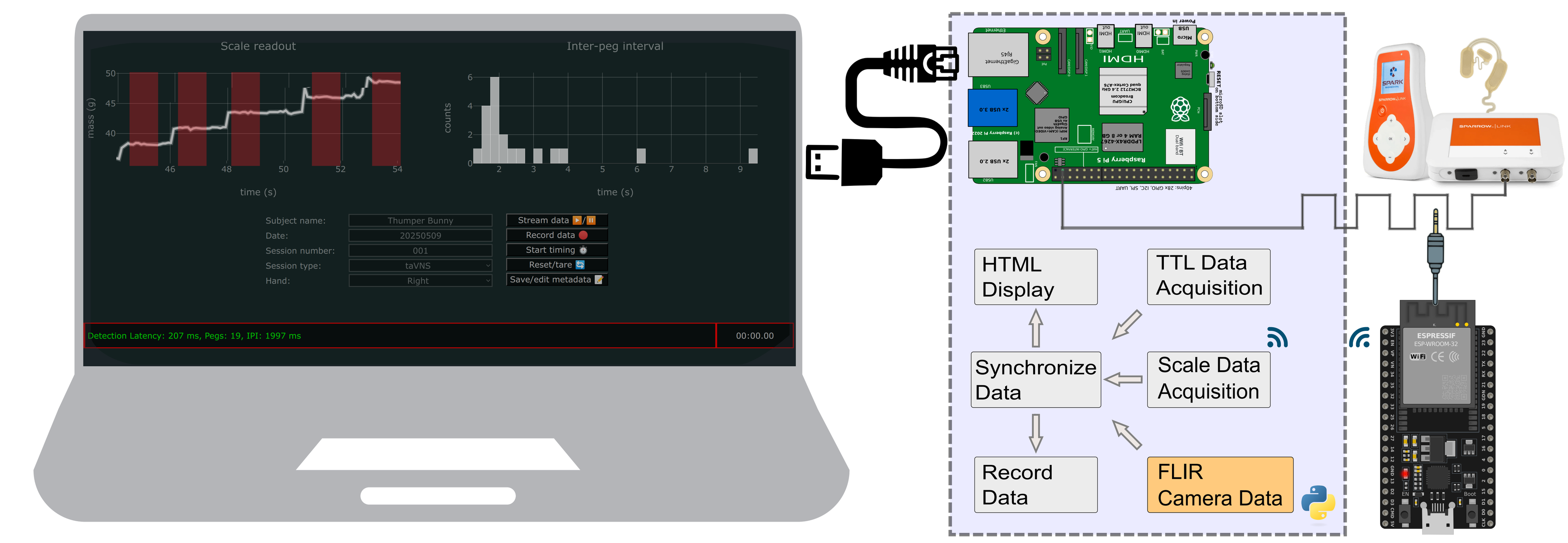
98% of closed-loop trigger latencies fall between 213-215 ms.



Acknowledgements

This work was funded by the University of Colorado Spark REACH.
The authors kindly thank Joshua Chu, PhD and James Webb, MD, PhD of NeuralAscension LLC for their assistance in system development.

System software



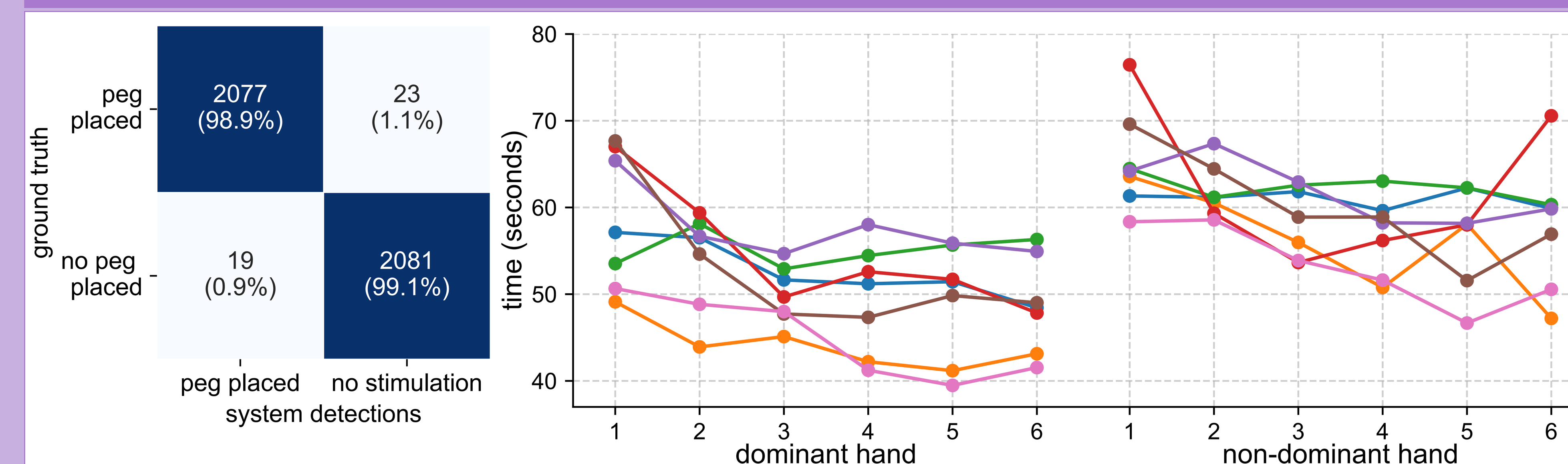
The system runs on a server-client architecture, with the Raspberry Pi acting as the central server.

- **Data Acquisition:** Raspberry Pi acquires data from the ESP32 via two channels (1) Wired TTL Trigger for confirmed peg placement and (2) Wireless Scale Data - a continous sampling from wirelessly from the ESP32 and load cell amplifier.

- **Data Processing:** The server software synchronizes the time-stamped TTL triggers with the incoming scale data and logs it to a single file.

- **Experimener GUI:** The Raspberry Pi hosts a web-based GUI that provides (1) Real-time plotting of weight data with stimulation periods highlighted, (2) live histogram of inter-peg intervals and (3) Session controls (start/stop, recording) and metdata entry.

Results



The system's performance in detecting successful peg placements was evaluated in 7 generally healthy participants.

- Robust detection accuracy, sensitivity, specificty and reliability are shown in the confusion matrix.
- The system successfully captured established behavioral patterns, tracking both learning effects (decreasing completion times across trials) and inter-hand performance differences (non-dominant hand typically slower than dominant).
- As expected in this healthy cohort, the stimulation condition (taVNS vs. sham) did not affect task performance.

Discussions & Conclusions

- **Validated System:** High accuracy sensorized GPT system with minimal latency.
- **Platform reliably captures key behavioral metrics:** e.g., learning effects and inter-peg intervals
- **Current Limitation:** The weight-based system is susceptible to false positive detections from non-placement impacts, such as jostling the board, which may be more common in populations with motor deficits.
- **Future Direction:** Integrate camera & computer vision to enhance robustness and reject false positive detections.
- **Vision:** The system's portability and rich data capture pave the way for future at-home personalized therapies, where machine learning models could dynamically adjust stimulation based on real-time performance.

Disclosure

Shayok Dutta receives monetary and equity compensation from NeuralAscension LLC, the company that engineered the system described in this manuscript.